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Femtosecond pulses at 50-W average power from an Yb:YAG planar waveguide amplifier seeded by an Yb:KYW oscillator

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Abstract: We report the demonstration of a high-power single-side-pumped Yb:YAG planar waveguide amplifier seeded by an Yb:KYW femtosecond laser. Five passes through the amplifier yielded 700-fs pulses with average powers of 50 W at 1030 nm. A numerical simulation of the amplifier implied values for the laser transition saturation intensity, the small-signal intensity gain coefficient and the gain bandwidth of 10.0 kW cm^{-2}, 1.6 cm^{-1}, and 3.7 nm respectively, and identified gain-narrowing as the dominant pulse-shaping mechanism.

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OCIS codes: (140.4050) Mode-locked lasers; (140.3280) Laser amplifiers.

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1. Introduction

Ultrafast lasers currently occupy a limited niche in scientific and industrial applications that has yet to be expanded into a more general industrial materials processing context. For this to happen there is a requirement for ultrafast laser systems capable of generating high average powers (>100 W), together with an appropriate combination of repetition rate, pulse energy, cost, complexity and physical size. Master-oscillator-power-amplifier (MOPA) configurations present a favourable route to this destination because they conveniently decouple the critical characteristics of the modelocked oscillator (high-quality pump beams, tight intracavity focusing, long resonators, nonlinear-optical components) from those of the amplifier (large modal areas, high-power and high-M^2 pump lasers). Several different MOPA configurations employing a variety of gain materials have been researched [1–4], however for the efficient generation of average powers above 100 W with pulse durations in the sub-picosecond region, the use of an ytterbium-doped gain medium (especially Yb:YAG) is currently the best choice from the standpoint of both the material's physical characteristics and the availability of suitable high-power diode lasers for pumping in the required 940 – 980-nm wavelength range. Planar-waveguide Yb:YAG amplifiers have high gain and excellent thermal properties because of their large surface area to contained volume ratio, and can be readily configured for non-overlapping multiple-pass amplification. This technology has been shown to be scalable up to 16 kW of continuous-wave (CW) output power, illustrating the potential of this geometry as a high-power amplifier [5]. Indeed, the planar waveguide amplifier which is the subject of the present work has already been shown to be capable of a single-pass small-signal gain as high as 1.5 cm^{-1} and, configured as an oscillator with double-sided pumping, produced 400 W output power with a slope efficiency of 78% [6].

Passively-modelocked diode-pumped laser oscillators based on ytterbium-doped monoclinic double tungstates (principally Yb:KYW and Yb:KGW) are becoming established as versatile and reliable sources of sub-200 fs pulses [7, 8], and are ideal candidates as seed sources for Yb:YAG amplifiers. The broad emission bandwidth of these materials allows the generation of ultrashort pulses in the 1020 – 1060 nm region, permitting tuning to the Yb:YAG gain peak at 1030 nm, and their absorption band at 981 nm matches a wavelength where high-brightness laser diodes are readily available as pump sources [9]. Yb:KYW and Yb:KGW are characterized by high emission cross sections which are essential for efficient passive modelocking, and the predominant approach is to use semiconductor saturable absorber mirrors (SESAMs) for this purpose because of the enhanced stability and less stringent cavity alignment which they enable.

We present here the first results from a MOPA based on an Yb:YAG planar waveguide amplifier seeded by pulses directly from a femtosecond Yb:KYW laser. The configuration achieved an average output power of more than 50 W at repetition frequencies of 53 MHz and pulse durations of around 700 fs, and a corresponding numerical simulation predicts scaling to 90 W with the implementation of doubled-sided pumping.

2. Experimental configuration

2.1 Yb:KYW oscillator

The implemented laser configuration is shown in Fig. 1. The pump laser was a collimated, beam-shaped laser-diode array (*Apollo C32-981-0*) with a linearly polarized output tunable to 981 nm, capable of generating 26.5 W at a drive current of 40 A (at 25°C), with a beam-quality parameter of $M^2 = 16$. The pump beam was focused by a 75-mm lens into a 10-mm-long Brewster-cut Yb:KYW crystal, doped at 1.5 at.%. The crystal was oriented for propagation along the $b(N_p)$ axis with its polarization parallel to the crystallo-optic N_m axis.

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The cavity was designed with a $1/e^2$ laser-cavity mode spot radius in the crystal of 100 µm, to optimally mode match the pump beam into the gain crystal. One arm was terminated by a 1.5% absorbance, SESAM with a 0.8% modulation depth (*BATOP GmbH*). For CW operation this SESAM was replaced with a high reflector (HR). The opposite arm of the cavity was terminated by a 10% output coupler giving emission centred at 1036 nm. To match the laser oscillator output wavelength with the emission peak of the Yb:YAG amplifier a 15% output coupler was used to shift the oscillation wavelength from 1036 nm to 1032 nm, making use of the non-saturated re-absorption losses in the Yb^{3+} quasi-three level gain system to achieve this shift in wavelength [10]. This increase in loss forces the wavelength to shift to a region where the gain cross-section is larger so that the same net gain can be sustained. For the Yb^{3+} gain system the laser is forced to operate at shorter wavelengths.

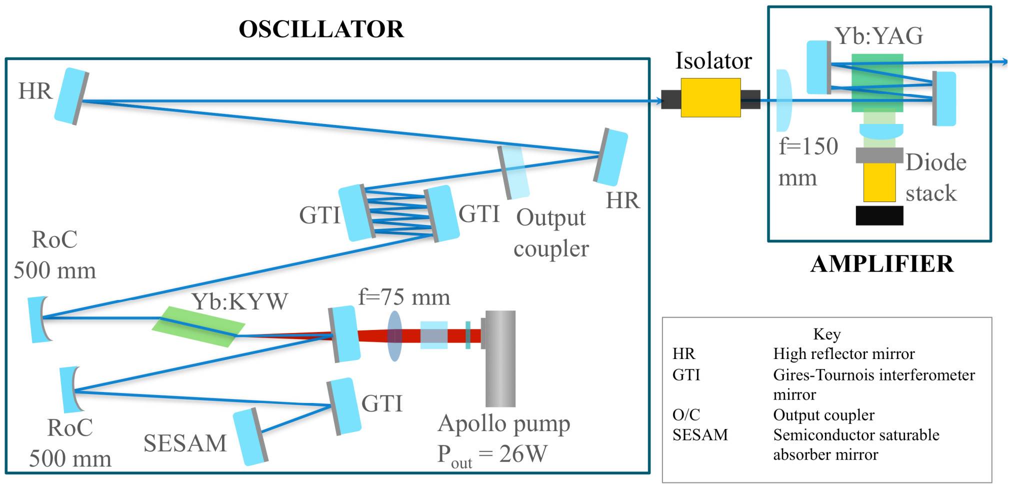

Fig. 1. Schematic of the Yb:KYW oscillator and Yb:YAG slab-waveguide amplifier.

Although the parameters required for a stable resonator were calculated with an ABCD matrix formalism, a large thermal lens in the Yb:KYW crystal required a cavity adjustment for optimal performance. To improve the output power and to compensate for the dispersion inside the cavity, a pair of Gires-Tournois interferometer (GTI) mirrors was implemented (coated for high reflectivity of 99.9% across 970 – 1120 nm). These mirrors had a GDD of -1300 ± 150 fs^2 per bounce, with a total of 5 bounces on each GTI mirror. One additional GTI with a GDD of -800 ± 100 fs^2 was used as a folding mirror in the short arm of the cavity. All the mirrors had 95% transmittance from 979 – 983 nm and >99.96% reflectivity at 1035 nm.

2.2 Yb:YAG planar waveguide amplifier

The planar waveguide used for this work consisted of a 150-µm-high 2% doped Yb:YAG planar waveguide core with 1-mm-high sapphire claddings of 13 mm length and 12 mm width and was fabricated by *Onyx Optics Inc.* and is described in more detail in ref [6]. This planar waveguide had a pump absorption of ~0.4 cm^{-1} [6]. Compared with [6], our system used single-sided pumping from a 6-bar diode-laser stack (*nLight Corporation*), capable of producing a 450 W line-focus through the use of a custom aberration-correcting phase-plate. This was directed onto one side of the waveguide facet giving an incident pump intensity of 22 kW cm^{-2}, significantly greater than the 2.8 kW cm^{-2} required for transparency in Yb:YAG. The laser oscillator required an optical isolator to prevent feedback from the amplifier; without isolation, feedback caused the wavelength of the oscillator to shift to a wavelength that did not overlap well with the peak of the gain in Yb:YAG.

The Yb:KYW beam was first formatted using a demagnifying telescope to vary the lateral (unguided) beam-size within the amplifier and then mode-matched into the planar waveguide using an f = 150 mm cylindrical lens. The $1/e^2$ mode diameters along the guided and unguided axes of the waveguide were 130 µm and 1.8 mm respectively. The amplifier folding scheme comprised two R = −15.5 mm, 95% reflectivity cylindrical mirrors. These created a plane-plane folding system in the unguided direction, which maintained a near-constant width along the unguided axis. In the transverse direction laser resonators for planar waveguide lasers with non-contacting mirrors should conform to one of the three low-loss coupling cases identified by Degnan and Hall [11]. In the guided direction we achieved Case-III waveguide coupling, thereby propagating the beam through the amplifier as a fundamental waveguide mode. The Case III condition consists of a mirror with curvature of two times the Rayleigh range of the beam placed one Rayleigh range from the waveguide facet. This design offers excellent mode selectivity, only efficiently coupling the fundamental waveguide mode back into the core. The Rayleigh range for this particular planar waveguide is 8 mm. The 95% reflectivity was chosen to reduce the likelihood of damage resulting from accidental CW laser oscillation during the alignment process.

3. Results and discussion

3.1 MOPA characteristics

In CW operation the oscillator produced 5.5 W of output power with an M^2 = 1.2 and a slope efficiency of 30%. In this configuration the laser was tunable between 1020 – 1057 nm. With the SESAM installed, modelocked operation yielded 480-fs pulses ($sech^2$ (t) pulse shape assumed) with a repetition frequency of 53 MHz. The spectral bandwidth was 2.6 nm, and the duration-bandwidth product was 0.39. The typical modelocked average output power from the oscillator was 4.5 W at 1032 nm which has good overlap with the Yb:YAG emission peak. After passing through the optical isolator and waveguide coupling optics, losses from these elements gave 3.5 W available for amplification.

Table 1. Summary of MOPA characteristics after each pass through the amplifier

Passes through amplifier	Pulse duration (fs)	Mode-locked output power (W)	Bandwidth (nm)	Pulse energy (µJ)
Oscillator only	465	3.5	2.6	0.066
1 pass	571	11	2.4	0.2
2 passes	596	23	not measured	0.43
3 passes	660	35.1	2	0.66
5 passes	703	50	2	0.94

Single-sided-pumping amplification with 1, 2, 3 and 5 passes through the amplifier generated output powers from the amplifier of 12 W, 26 W, 34 W and 40 W respectively, when the laser was operated in the CW regime with a 1-mm diameter beam in the unguided direction. This shows the onset of saturation due to the small beam width. In the modelocked case the beam diameter was increased to 1.8 mm to reduce saturation, this gave output powers of 11 W, 23 W, 35 W and 50 W for 1, 2, 3 and 5 passes respectively. Figure 2(a) shows how the measured optical spectrum generated by the amplifier narrowed as the number of passes through the waveguide increased. This gain narrowing is characteristic of amplifying femtosecond pulses and, along with the linear chirp accumulated with each pass of the Yb:YAG planar waveguide, explains why the pulse durations increased on each pass. Figure 2(b) illustrates how the pulse duration increased from 480 fs to 700 fs as the number of passes through the amplifier were increased.

Beam quality effects in the amplifier require consideration separately in the two axes. In the non-guided direction, the folded beam is effectively parallel over the total length in the folded amplifier (Rayleigh range Z_R = 2m), and thermal lensing is a weak effect. The beam width is not significantly changed by amplification and M^2 is not expected to degrade relative to the input value. Beam steering from the temperature gradient using the present single-sided

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pumping is the main issue but has not yet been quantified. In the guided direction, transverse thermal lensing is not expected to degrade the fundamental guided mode for the pump power density and core size used [12]. Additionally, the repeated mode-selective coupling by the cylindrical fold mirrors acts to stabilize the beam properties. Whilst the unguided beam issues are similar to free-space slab amplifiers [3], the use of a waveguide gain section has the advantage of allowing scaling of the amplifier length with freedom from transverse thermal degradation of the beam [5].

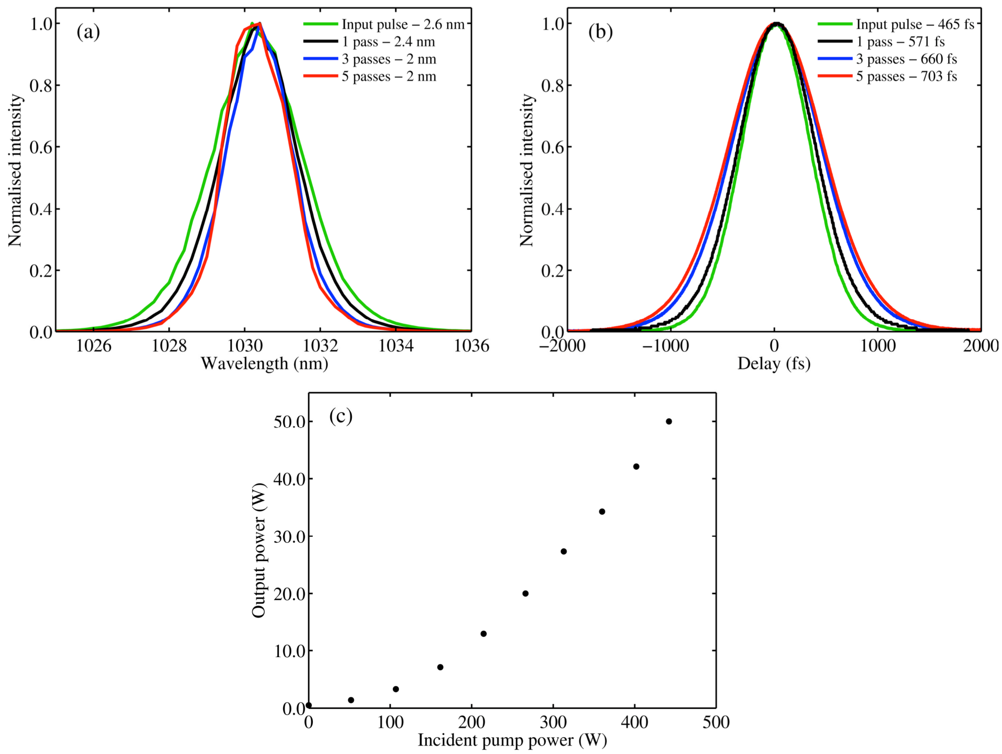

Fig. 2. (a) Narrowing of the optical spectrum with increasing numbers of passes through the amplifier. (b) Intensity autocorrelation showing a corresponding increase of the pulse duration. (c) Average output power in the 5-pass configuration.

Without beam folding mirrors, the planar waveguide section is free of internal parasitic oscillations [6, 13]. The folding mirrors are adjusted to create a wedge angle in the non-guided plane to prevent parasitic oscillation, but consequent beam walk-out limits the number of passes to 5 in the amplifier width. The degree of gain saturation established in section 3.2, reduced pump absorption in a non-saturated amplifier [6] and incomplete filling of the amplifier volume are responsible for a lower power and efficiency of the current MOPA configuration relative to previous CW oscillator results [6].

Ultimately, 5 passes through the amplifier yielded a maximum output power of 50 W (Fig. 2(c)), giving a pulse energy of ~1 μJ. Scaling to higher energies will require more passes through the gain medium, which can be achieved by using toroidal mirrors [14], while still suppressing parasitic oscillation.

3.2 Saturation and pulse-shaping effects in the amplifier

During amplification, the pulses are subject to several competing shaping processes, including group-delay dispersion, gain narrowing, gain saturation and self-phase-modulation. The influence and relative importance of these processes was investigated by modelling the propagation of the pulses through the amplifier by using:

$$\frac{\delta A}{\delta z} = gA + \sum_{k \geq 1} i^{k+1} \frac{\beta_k}{k!} \frac{\delta^k A}{\delta t^k} + i\gamma |A|^2 A, \tag{1}$$

where $A(z, t)$ is the field envelope expressed in dimensions of √power, t is time in the co-moving pulse frame, γ is the nonlinear coefficient of Yb:YAG per unit area, and β_k is the k^{th}-order dispersion parameter of Yb:YAG. The saturation of the amplifier gain was modelled as,

$$g = \frac{g_0}{1 + \frac{1}{T_R a I_{SAT}} \int_{-T_R/2}^{T_R/2} |A(t')|^2 \, dt'} \tag{2}$$

with go being the small-signal amplitude gain, TR the pulse repetition period, a the beam area and Isat the amplifier medium saturation intensity. We included gain-narrowing effects by treating the small-signal gain as a Gaussian distribution about 1030 nm, with a full-width half-maximum bandwidth of $\Delta\lambda_g$.

A feature of our model is the inclusion of the laterally-resolved gain coefficient for our pump geometry. Under single-sided-pumping conditions, the lateral pump profile follows a typical Beer's Law decay, matching the rate expected for the 2% doping concentration of the Yb:YAG gain medium [6]. The seed beam is injected into the waveguide closest to the side on which the pump light is incident. As it progresses along a folded path, making multiple transits of the waveguide and moving away from the most intensely pumped region, the seed beam experiences a lower gain coefficient for each subsequent pass. In a previous experiment [13] we measured a decrease in the small-signal intensity gain coefficient from 1.3 cm^{-1} to 0.4 cm^{-1} across the aperture of the waveguide, corresponding to a 20% reduction after each transit of the waveguide. We included this effect in our model, along with a 10% loss per pass to account for the 95% reflectivity of the folding mirrors combined with a 5% coupling loss.

The numerical model was configured to fit the experimental data shown in Table 1, which lists the pulse energy, bandwidth and duration for 0 to 5 passes of the amplifier. Fitting was implemented using a Nelder-Mead algorithm which minimized the root-mean-squared error between the model and the experimental values of pulse energy and duration. The algorithm treated I_{sat}, g_o and $\Delta\lambda_g$ as free variables and adjusted them to obtain the best agreement. These results are presented in Fig. 3. This procedure resulted in values for the saturation intensity of 10.0 kW cm^{-2}, the small signal intensity gain coefficient of 1.6 cm^{-1}, and the gain bandwidth of 3.7 nm. All of these results are close to the expected values of 9.5 kW cm^{-2} [15], 1.5 – 2.0 cm^{-1} [6] and ≤ 5 nm (at high inversion levels) [16].

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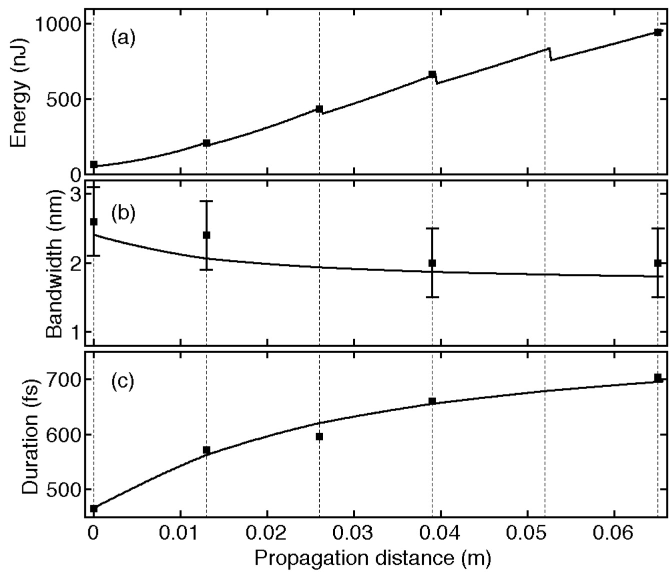

Fig. 3. Numerical modelling results (solid lines) fitted to experimentally measured pulse parameters (symbols) by adjusting E_{sat}, g_o and $\Delta\lambda_g$. Propagation between neighboring dashed vertical lines represents one pass through the 13-mm-long Yb:YAG crystal. The error bars in (b) represent the ± 0.5 nm accuracy of the spectrometer used to record the pulse spectra.

The contributions of dispersion, nonlinearity and gain were examined by using the model to switch these individual effects on and off. Self-phase-modulation effects were negligible, and group-delay dispersion was found to contribute only a few fs of pulse broadening over the 65-mm propagation distance corresponding to 5 passes through the amplifier. The choice of the gain narrowing and gain saturation parameters sensitively affected the quality of the fit to the experimental data, allowing us to conclude that these dominated the pulse-shaping mechanisms in the amplifier.

Using the results retrieved from the fitting procedure we were able to simulate the effect of future changes to the experimental conditions. For example, by replacing the existing mirrors with high reflectors and implementing double-sided pumping we predict an average output power of 90 W and a pulse duration of 735 fs.

4. Conclusions

In summary we have reported the first use of an Yb:YAG planar waveguide amplifier for ultrafast pulse amplification by combining it with a high-average-power Yb:KYW femtosecond oscillator. The amplifier produced 700 fs duration pulses at average powers in excess of 50 W and at a repetition frequency of 53 MHz. Future work will concentrate on scaling to higher pulse energies and higher average output powers at repetition frequencies in the 100 kHz to multi-MHz range. Pumping the planar waveguide amplifier from two sides has been demonstrated in CW operation and is predicted to extend the performance of the existing configuration to average output powers of 90 W. By using toroidal mirrors we expect to be able to achieve 9 passes of the waveguide without risk of oscillation, which combined with double pumping should achieve around 165 W of output power.

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